Towards a Conservative 50 T HTS Magnet for Final Muon Collider Cooling

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- Starting 50T Design
- Modified Design
- Quench Protection
- Increased Stabilizer
- 60 T
- YBCO
- Conclusion

Choice of HTS Material

Use American Supercon "High Strength"
0.27 x 4.3 mm

- American Superconductor Advantages:
  - Pre-reacted (like YBCO)
  - Available with ss cladding, strong
  - Relatively cheap (20\$/m)
  - BNL has experience using it
- Wind and react BSCCO materials have somewhat higher current capacity
  and will be studied by Fermi

High Current Density Wire

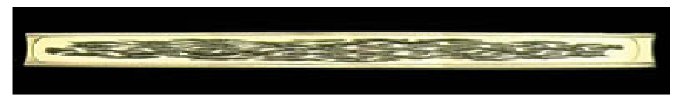
- Designed for use in applications where current density is the major design parameter such as in high performance coils and magnets

172 A/mm^2

High Strength Plus Wire

- High tensile strength
- High engineering current density

133 A/mm^2



Compression Tolerant Wire

- Withstands compressive strains
- High tensile strength
- High current

100 A/mm^2

Hermetic Wire

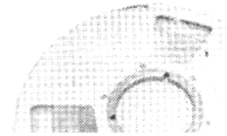
- Hermetically sealed
- High tensile strength
- High current

85 A/mm^2

YBCO from IGC

Higher current density, but cost not yet known

Second-Generation High Temperature Superconductor

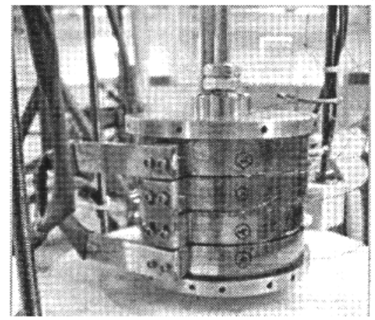


SuperPower has been developing YBCO-based second-generation (2G) HTS wire at its manufacturing plant in Schenectady, New York since 2000 and is now producing long lengths of high performance wire and **taking orders**.

Once SuperPower™ 2G HTS wire has been slit into device-specific widths, **Surround Copper Stabilizer (SCS)** is applied to completely encase the wire. Overcurrent capability in SCS wire can be tailored to the specific application. The stabilizer protects the conductor and produces rounded edges that are beneficial for high-voltage applications. Further, the probability of failure in the device due to voltage breakdown is reduced in conductors with SCS. SuperPower's SCS has been successfully implemented and tested on continuous lengths of hundreds of meters of wire.

SPEC	SCS 4050	SCS 12050
	SCS = Surround Copper Stabil	
Width	4	12
Thickness	0.095	0.095
Silver Overlayer Thickness	2	2
Copper Stabilizer Thickness	0.04	0.04
Substrate Thickness	0.05	0.05
Critical Tensile Stress	>550	
Yield Strength	1200	1200
Bend Diameter in Tension	11	

- New high field coils fabricated with 2G HTS wire have achieved a record magnetic field of 2.4 Tesla at 64K.



* Uniformity in long lengths of SuperPower 2G HTS Wire is better than 5%

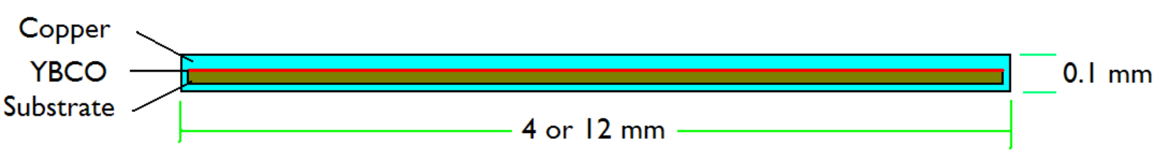
* Piece lengths of up to 300 meters are available

* Ic values range from 60 – 100 Amps at 77 K in 4 mm width

* Engineering Current Density (Je) = 16 – 26 kA/cm² 160-260 A/mm^2

** *Other custom configurations are also available.* **

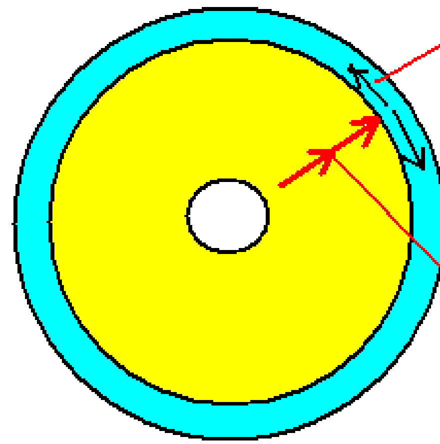
Additional product details available on our website: www.superpower-inc.com



Radial Force Constraint

If radial forces only constrained at outer radius then maximum radial pressure:

$$P_r \mathrm{max} \ = \ \int B(r)\ j\ dr$$



For a long solenoid:

$$j \ = \ \frac{dB}{dr}\,\frac{1}{\mu_o}$$

from which:

$$P_r \mathrm{max} \ = \ B^2\,\frac{1}{2\mu_o}$$

For B=50, and $\mu_o = 4\pi\ 10^{-7}$

$$P_r \mathrm{max} \ = \ 995 MPa$$

Compared with the compression strength of epoxy filled superconductor stacks of about 130 MPa. Clearly the radial forces must be constrained more locally.

Calculation of support material fraction

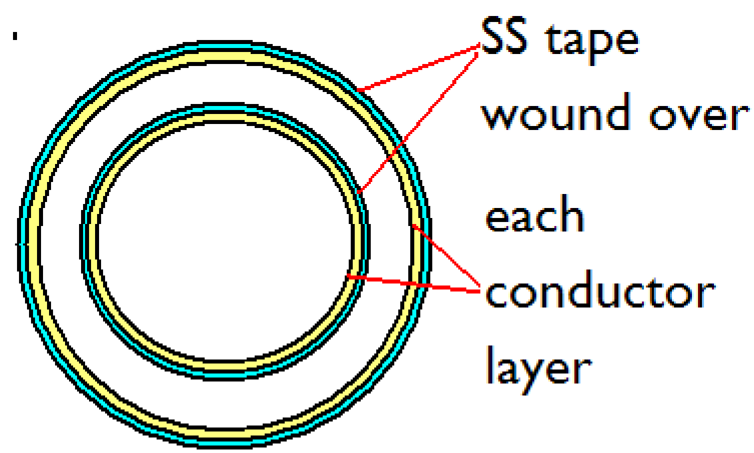
If the magnet is wound in layers, and stainless steel tape, or other materials are wound with the conductor, then we can size the tapes to restrain the radial forces allowing a strain equal to the maximum specified for the conductor (0.4% in this case). If the stainless steel fraction of the ss + sc cross section is α. then, with allowance for the estimated Young's modulus of the superconductor ($Y_{sc}\ =$), the tension per unit area T is:

$$T = j(1-\alpha)rB = (\alpha Y_{ss} + (1-\alpha)Y_{sc})\,S$$

from which

$$\frac{1}{\alpha} \;=\; 1 \;+\; \frac{jrB - Y_{sc}}{Y_{\text{ß}}\;S}\,.$$

α is a function of r



The field vs radius is then given by

$$\frac{dB}{dr} = j\alpha\mu_o$$

1) Starting Design (as reported in PAC paper)

- Assume magnet is wound in layers
- Assume 85% of currents for American Superconductor "High Strength" HTS Tape
  i.e. assume currents are adjusted layer by layer
  will later lamp into 16 currents
- Assume Stainless steel is added between layers to keep Strain < 0.4 %
  i.e. Stainless thicknesses added are adjusted layer by layer
- Set inside radius $= 2$ cm
- Assume that Stainless steel provides required insulation
  i.e. no allowance for insulation space
- Take HTS current density values even in NbSn or NbTi - conservative

Calculated Coil Radius

Using:

$\mathsf{Y}_{ss} = \ 192 \ \ (GN/m^2)$

$\mathsf{Y}_{sc} = \ 85.71429 \ \ (GN/m^2)$

S= .4 (%)

R0= 2 (cm)

j0= $117.8444 \ \times \ (3 \ - \ .03 \ B) \ \ \ (A/mm^2)$

we obtain

$r \ = \ 23.9cm$

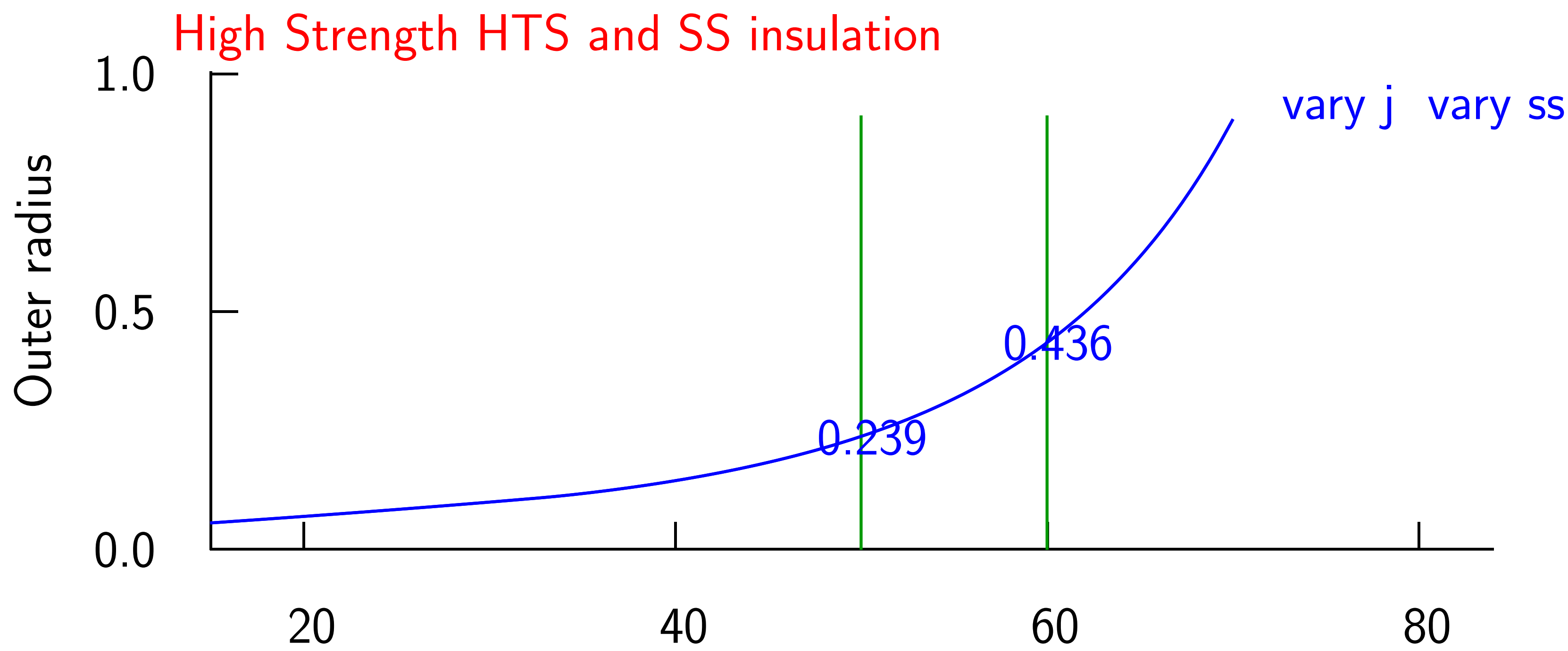
This can be compared with the PAC quoted radius of 23 cm. This difference is within the errors in the different estimats of the as yet unmeasured current density vs field.

Length of HTS conductor=61 km

cost of HTS conductor=1.2 M$

Outer coil radius vs. central axial field

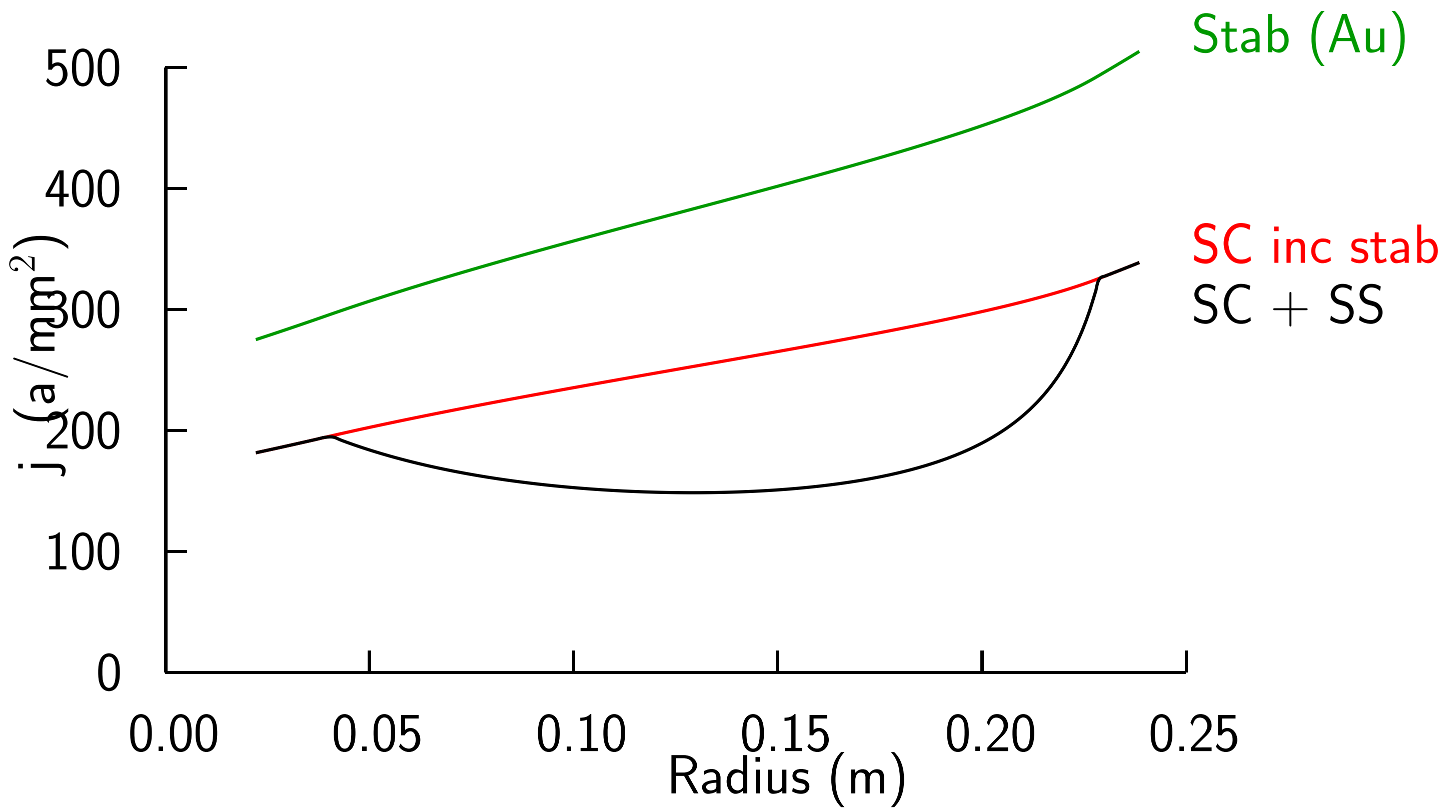
As a function of field the radii are:



These are surprisingly modest radii.
Even for 60 T the radius is only 44 cm

Current densities

Including that in the stabilizer after the SC is no longer superconducting



Axial Forces

$$dF_z \ = \ j \ B_r \ dr \ da \ dz$$

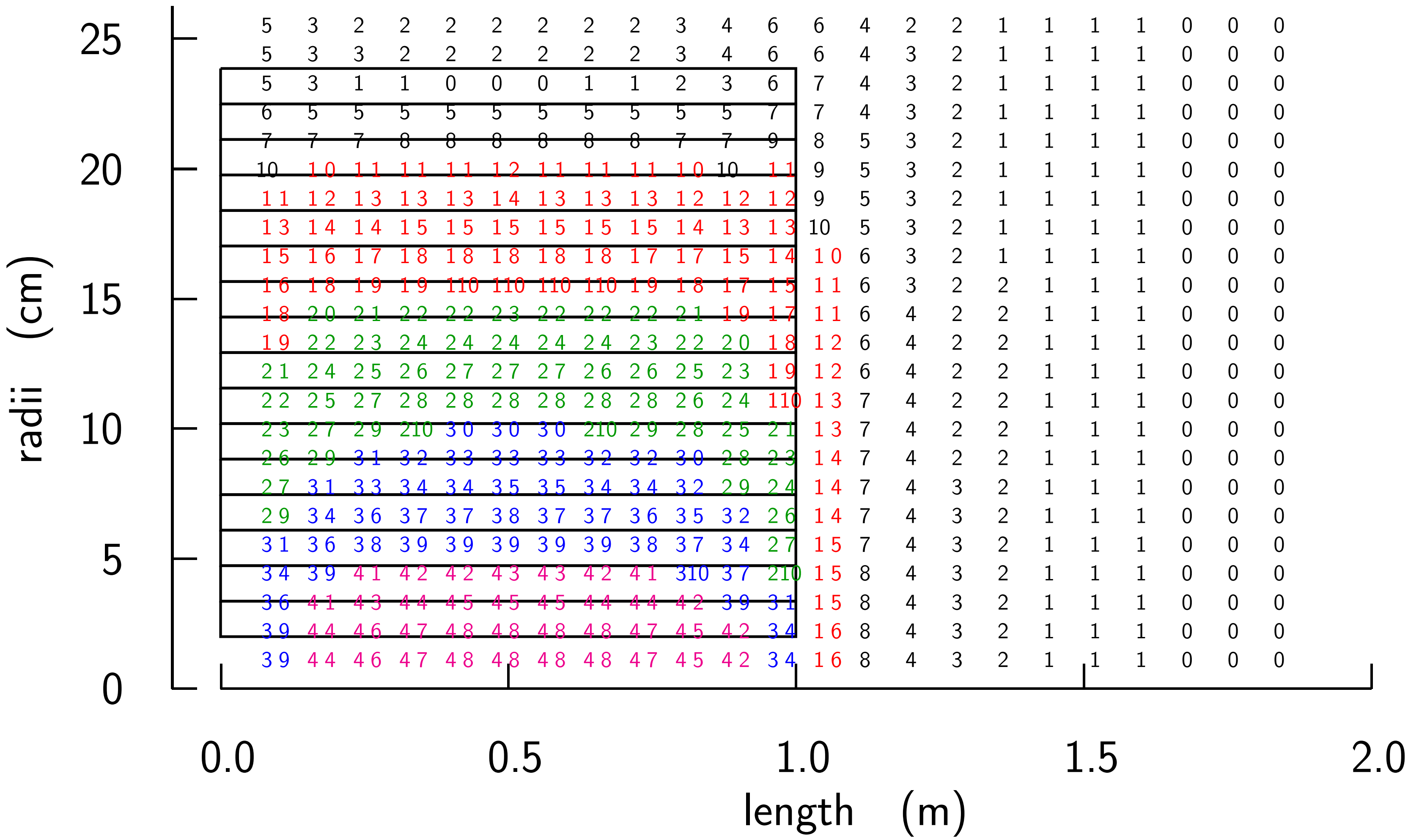
Axial pressure

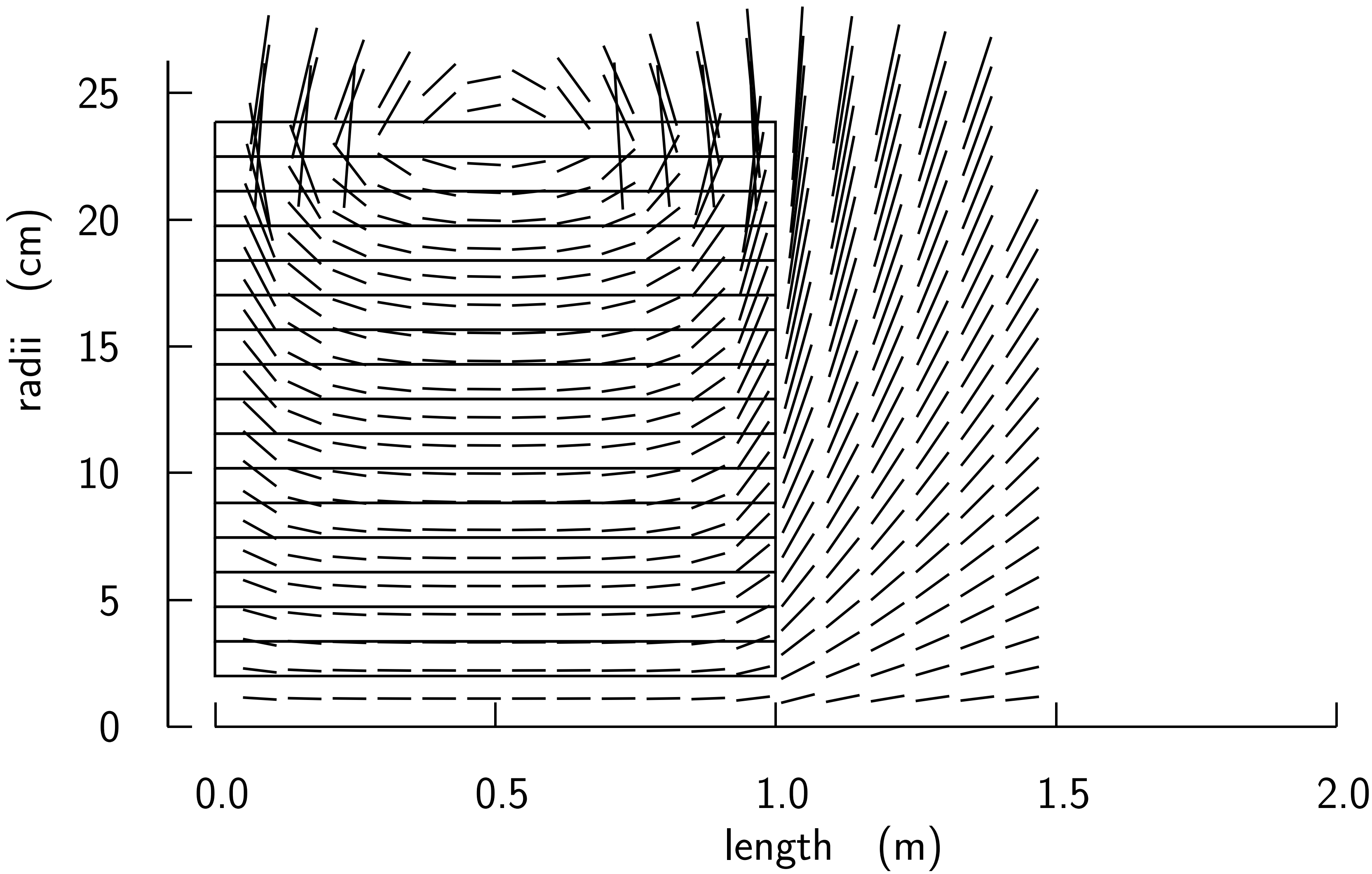
$$P_z \ = \ j \ \int_{z1}^{z2} \ B_r \ dz$$

If not subdivided then z_1 is at magnet center where forces ballance and z_2 is the half magnet length

Lump layers into 16 blocks and calculate fields:

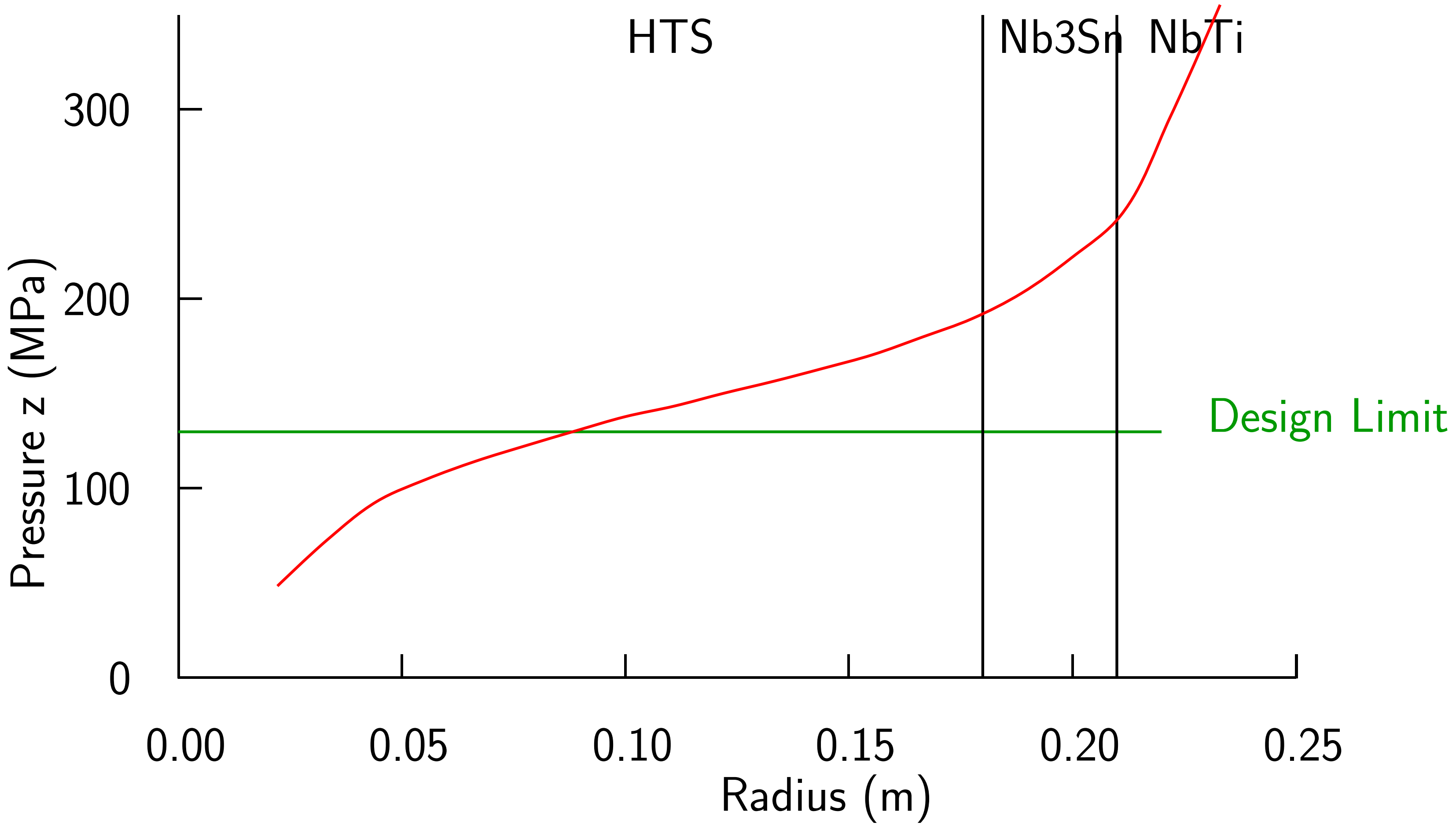
Fields





25
20
15
10
5
0
radii (cm)
0.0
0.5
1.0
1.5
2.0
length (m)

Axial pressure on layers



Note:

- These are very high (of order 40 k psi)
- Above reasonable limit of 130 MPa
- Especially in the Nb3Sn and NbTi

2) Modified Design to Control Axial Pressures

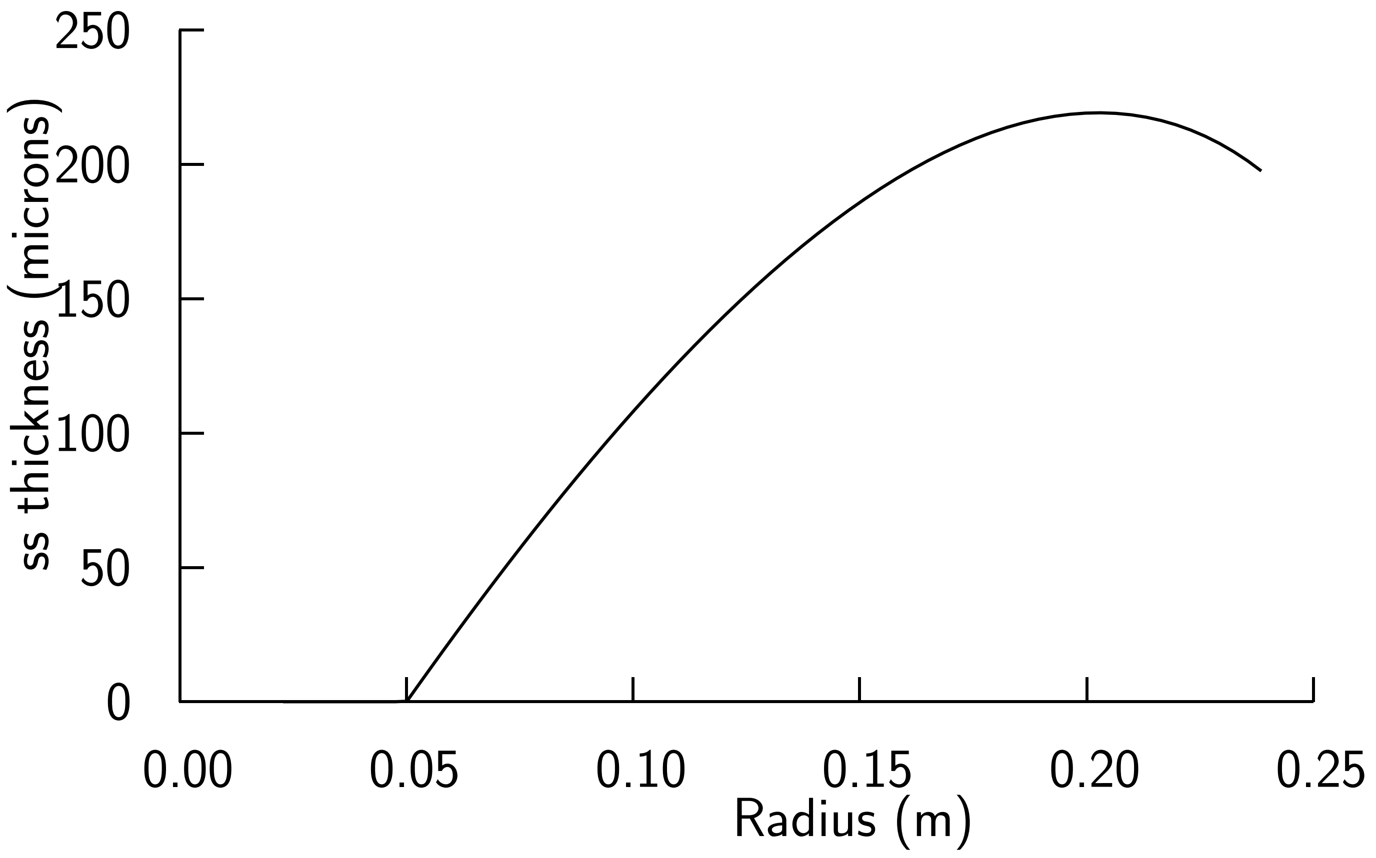
- Add 25 μm insulation to each tape - for ramp down
- Break outer conductor into blocks supported by ss discs & cylinders
  (Mc Inturf did this for LHC tripler, using 130 MPa limits)
- Wind them in pancakes & take radial force on outer ss rings
- Radial pressures are 91 MPa in NbSn, 33 MPa in NbTi ($\leq$ 130 MPa)
- This controls pressure in NbSn & NbTi, but leaves some excess in the HTS
- Lengthen the outer coils lowers the radial fields in the HTS
  by 'drawing' the field lines out

The resulting rdius is now 36.5 cm c.f. 24 cm

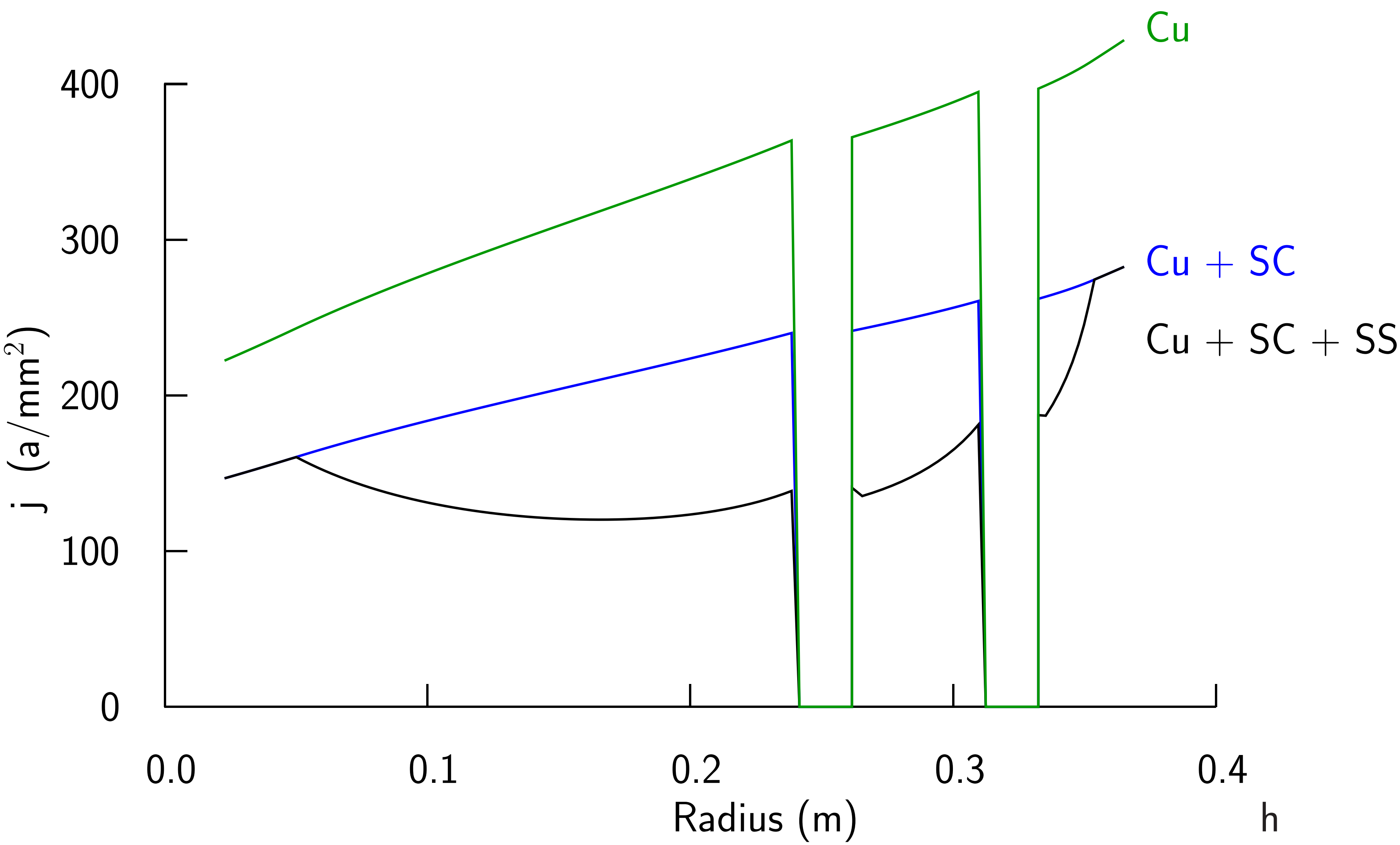
The HTS conductor length is now 81 km c.f. 61 km

The HTS conductor cost is now 1.6 M$ c.f. 1.2 M$

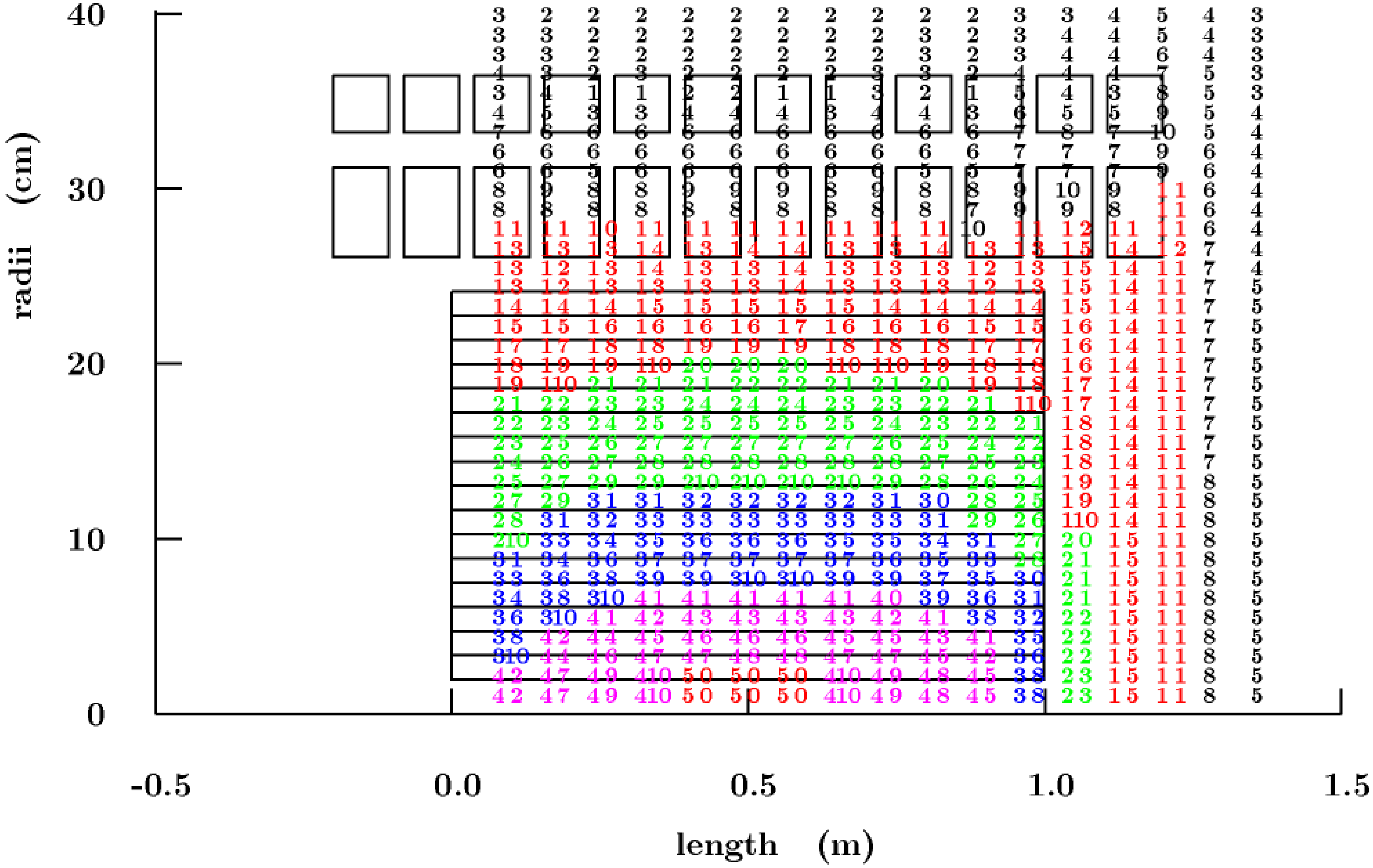
SS thickness

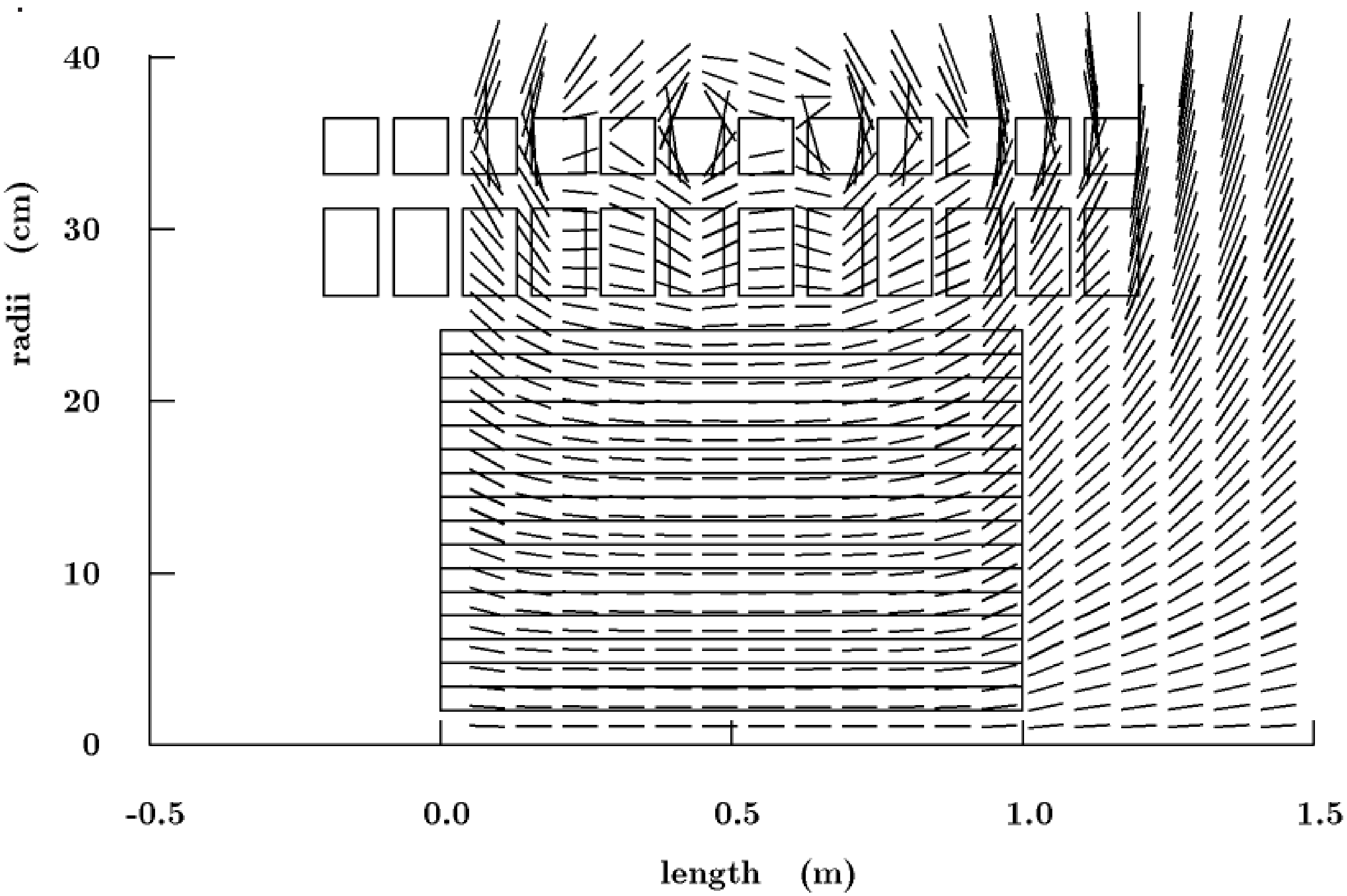


Current Densities

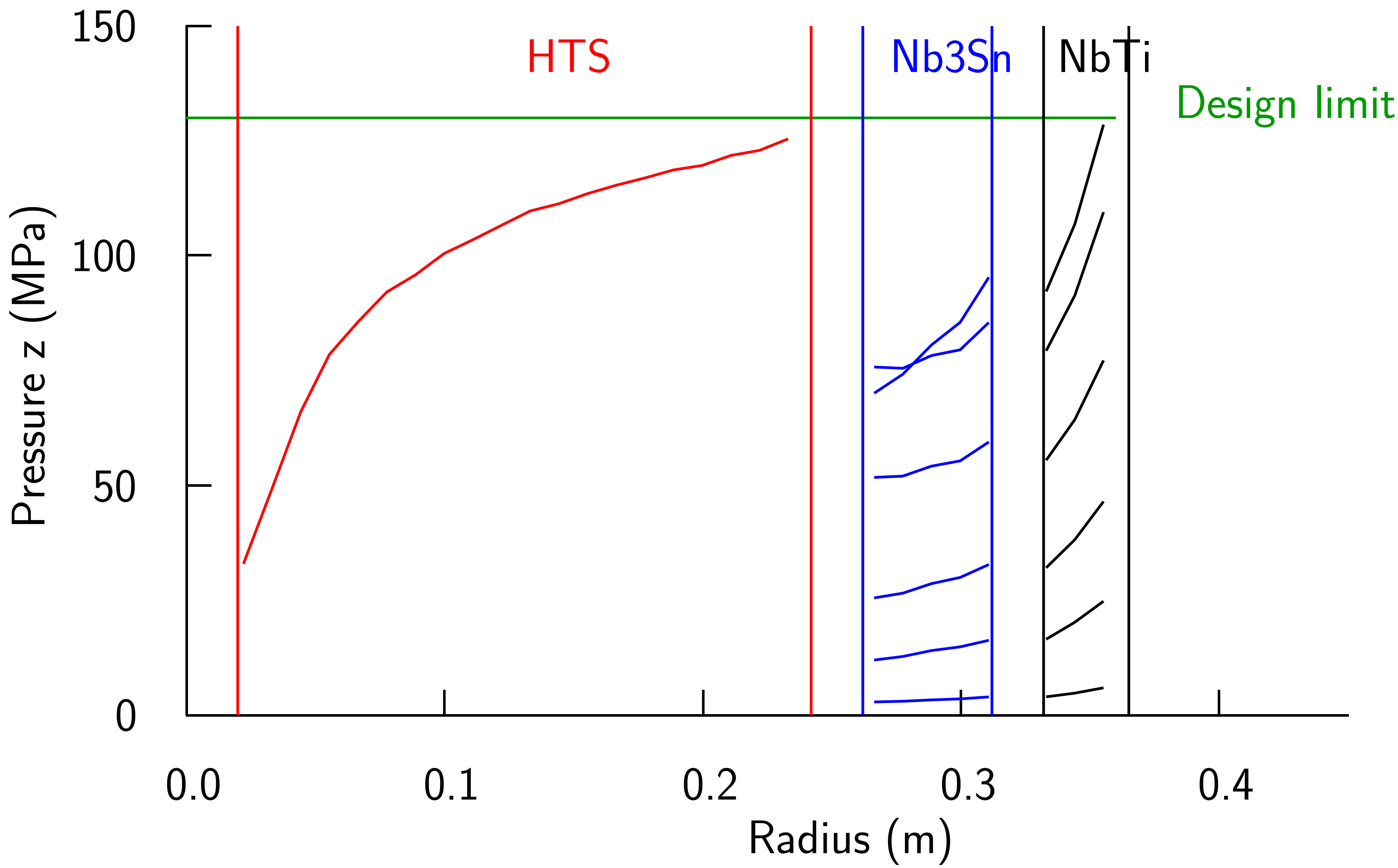


Fields for Force Calculations




40
30
20
10
0
radii (cm)
-0.5
0.0
0.5
1.0
1.5
length (m)

Axial Forces for Modified Design



- Axial forces are now within limit

Quench protection

- At local spot where quench starts, ignoring heat conduction, the local heating causes temperature to rise until current is stopped.
- In a high field solenoid the inductance is so high that a rapid turn off requires high voltages.

After a quench, all the local current will be flowing in the stabilizing material (Cu or Ag):

$$\frac{dT}{dt} = \frac{1/2\ j_{\rm Cu}^2\ \Omega(T)}{\Sigma(\alpha_i \rho_i\ S_i(T))}$$

where j is the current density in the stabilizing material, Ω is the specific resistivity of the stabilizing material, α_i are the area fractions of the other materials in the winding (SC, sructural stainless steel), ρ_i are the densities, and S_i are the specific heats.

Integration gives the temperature rise as a function of $\int j_{\rm Cu}^2 dt$

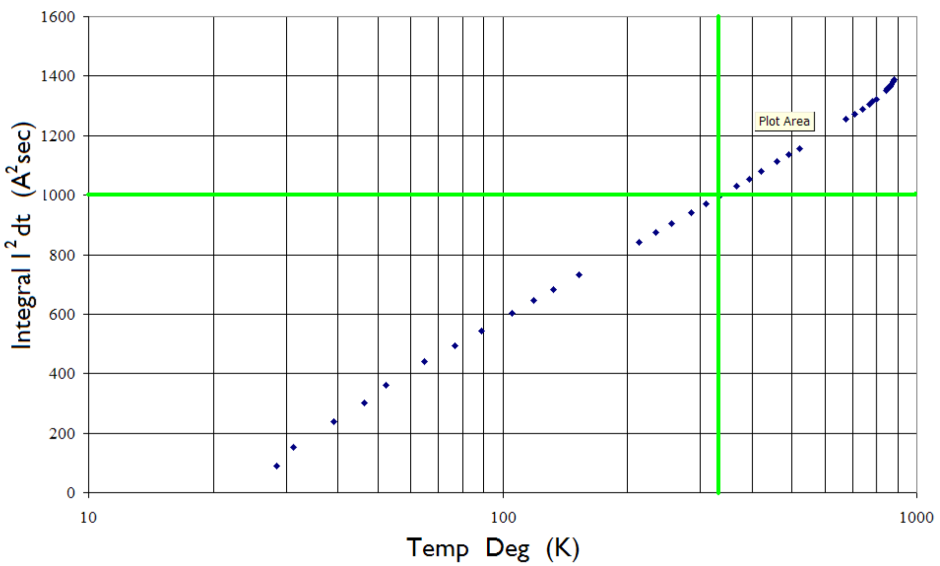
$$\Delta T = f[\int j_{\rm Cu}^2 dt]$$

where the f is a function of $\alpha_i,\ \Omega_{\rm Cu}(T),\ S_i(T),\ \text{etc.}$

Typical $\int I^2 dt$ vs. ΔT

To obtain an approximate values of f we take the calculated values if $T vs. \int I^2 dt$ for a specific wire (RHIC corrector) The figure below shows these values together with the derived values in terms of $\int j_{\rm Cu}^2 dt$.

Wire with $r = 0.33 \ \ \mathrm{mm}$ and 0.71 Cu/SC had $A_{\rm stab} \ = \ 0.61 \ \ \mathrm{mm}^2$



We limit the temperature rise to 100 degrees to avoid loss of ss strength during a quench

For 100 degrees: $\int I^2 \ dt \ \approx \ 500 \quad (\mathrm{A}^2 \ \mathrm{sec})$

corresponding to the integraal of current density squared of

$$\int j_{\rm stab}^2 \ dt \ = \ \frac{500}{[\pi(.33.2)^2 \ .71]^2} \ = \ 13.4 \ 10^4 \quad [(\mathrm{A}/\mathrm{mm}^2)^2 \ \mathrm{sec}]$$

Required ramp down rate

For an exponential decay of the current with a time constant τ then

$$j \;=\; j_o\, e^{-t/\tau}$$

$$\int j^2\, dt \;=\; \frac{1}{2}\, j_o^2\, \tau$$

For $j_o \;=\; 500$ A/mm^2, and $\int j^2\, dt \;=\; 13.4\ 10^4$ (A/mm^2)^2 sec then

$$\tau \;=\; 2\,\frac{\int j^2\, dt}{j_o^2} \;=\; 2\,\frac{13.4\ 10^4}{500^2} \;=\; 1.1 \quad \mathrm{sec}$$

The magnetic stored energy in this magnet is 57 MJ

Quench Protection (Ramp Down) Methods

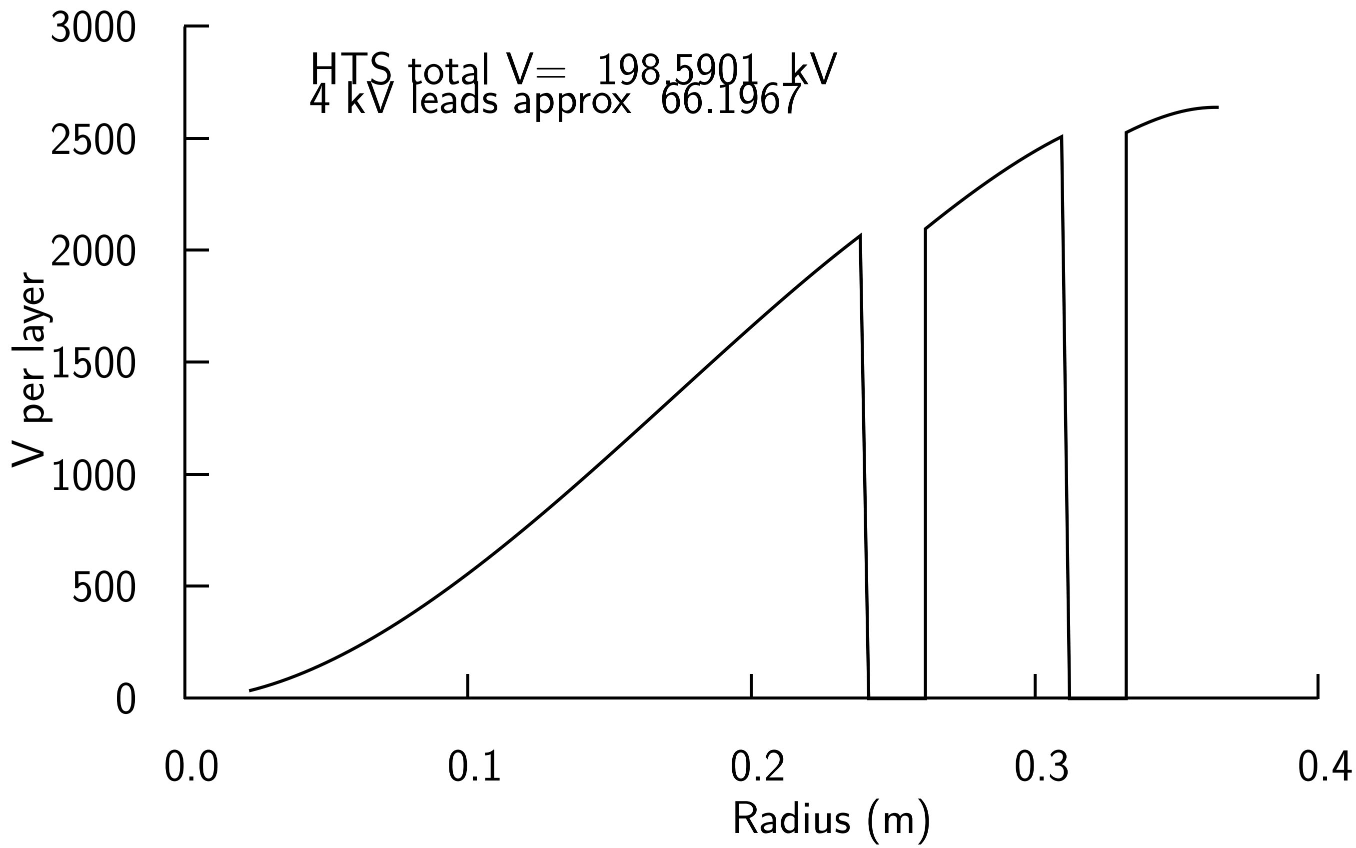
1. Passive   If quench propagates fast enough then the magnet current drops before the local spot overheats
   Unlikely for HTS   & all the energy ends up in the magnet
2. Added closed conducting loops that will carry the current as the superconductor currents drop (Alvin's suggestion)
   Requires considerable copper thus decreasing average density and increasing required radius and stored energy
   & all the energy ends up in the magnet
3. Active heaters
   Detect any quench and actively fire heaters to quench entire magnet causing rapid ramp down without large external voltages
   A significant temp jump must be introduced to quench HTS making this hard
   & all the energy ends up in the magnet
4. Active Ramp Down
   Detect any quench and actively ramp down magnet
   Some technique must be employed to avoid very large external voltages
   Most energy is extracted

Active Ramp Down

The voltage per double layer depends on the enclosed flux $\Phi(r)$

$$V = 2\,\frac{L\,\phi}{w\,\tau}$$

which is shown below for the HTS part (above 15 T):



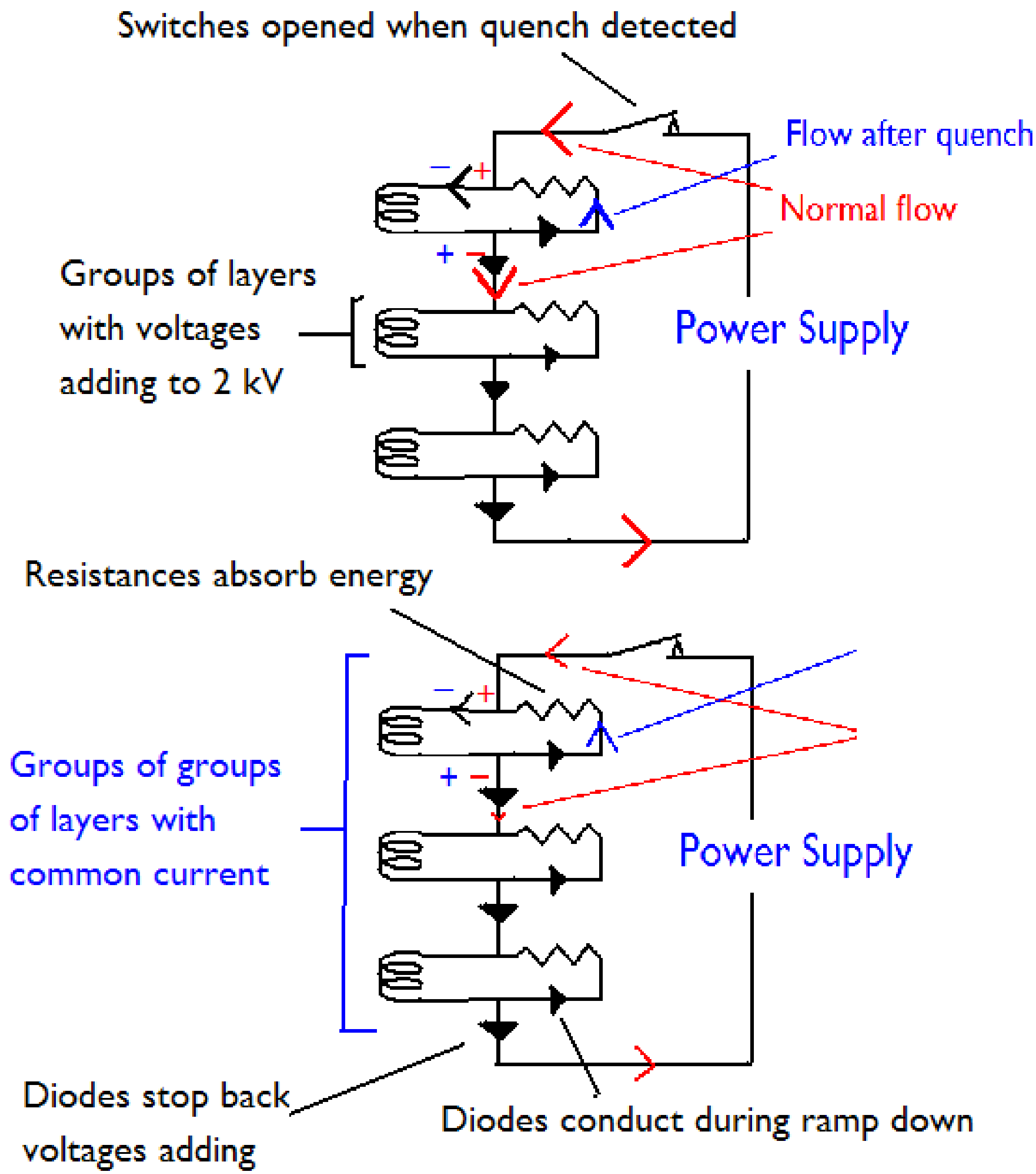
- Maximum layer to layer voltage is 2 kV Needing insulation, as provided

Voltage avoidance technique for Active Ramp Down

- For voltages of all leads $\leq$ 2 kV

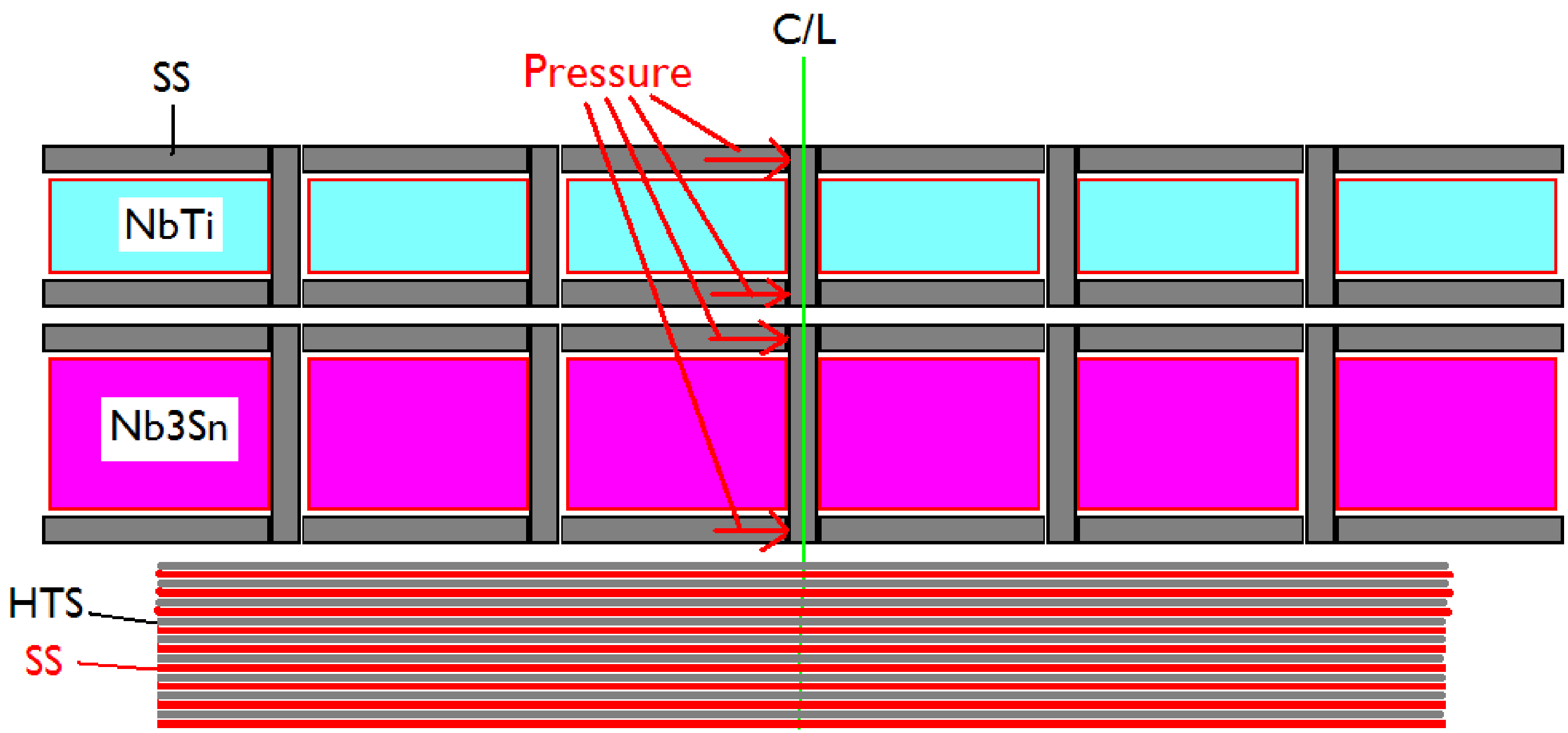
  Number of leads is 130

  Currents 180 to 280 Amps



Support Structure for Outer Coil Blocks

- If cylinder thicknesses 1 cm
- Axial loads on ss cylinders 310 amd 380 MPa for NbTi & NbSn
- Bending of plates and buckling of cylinders not studied

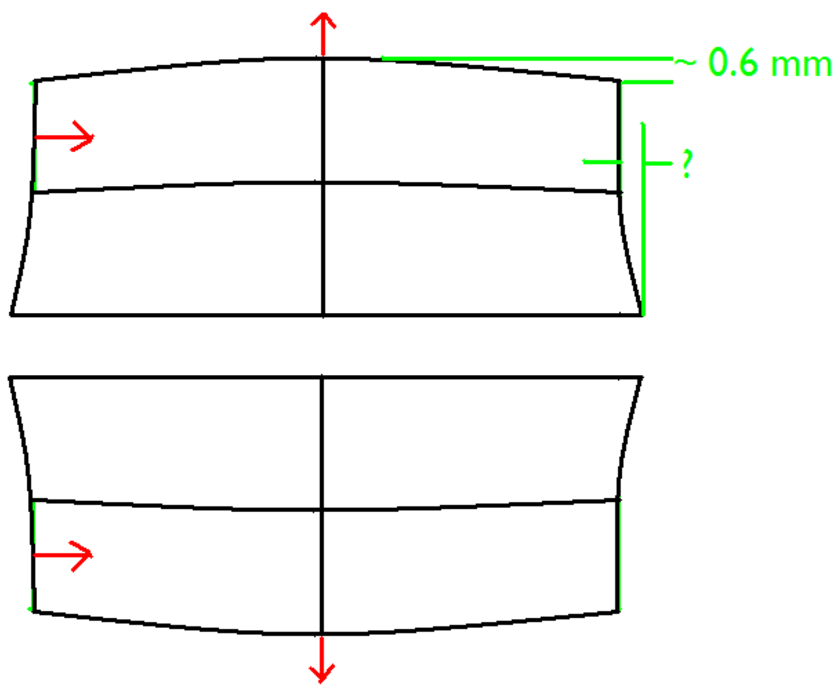


Shear forces on HTS layers

- central part of each coil layer increases rad by 0.4%
- But ends increase by only about 0.2%
- So there is a shear of about 0.6 mm between center and ends

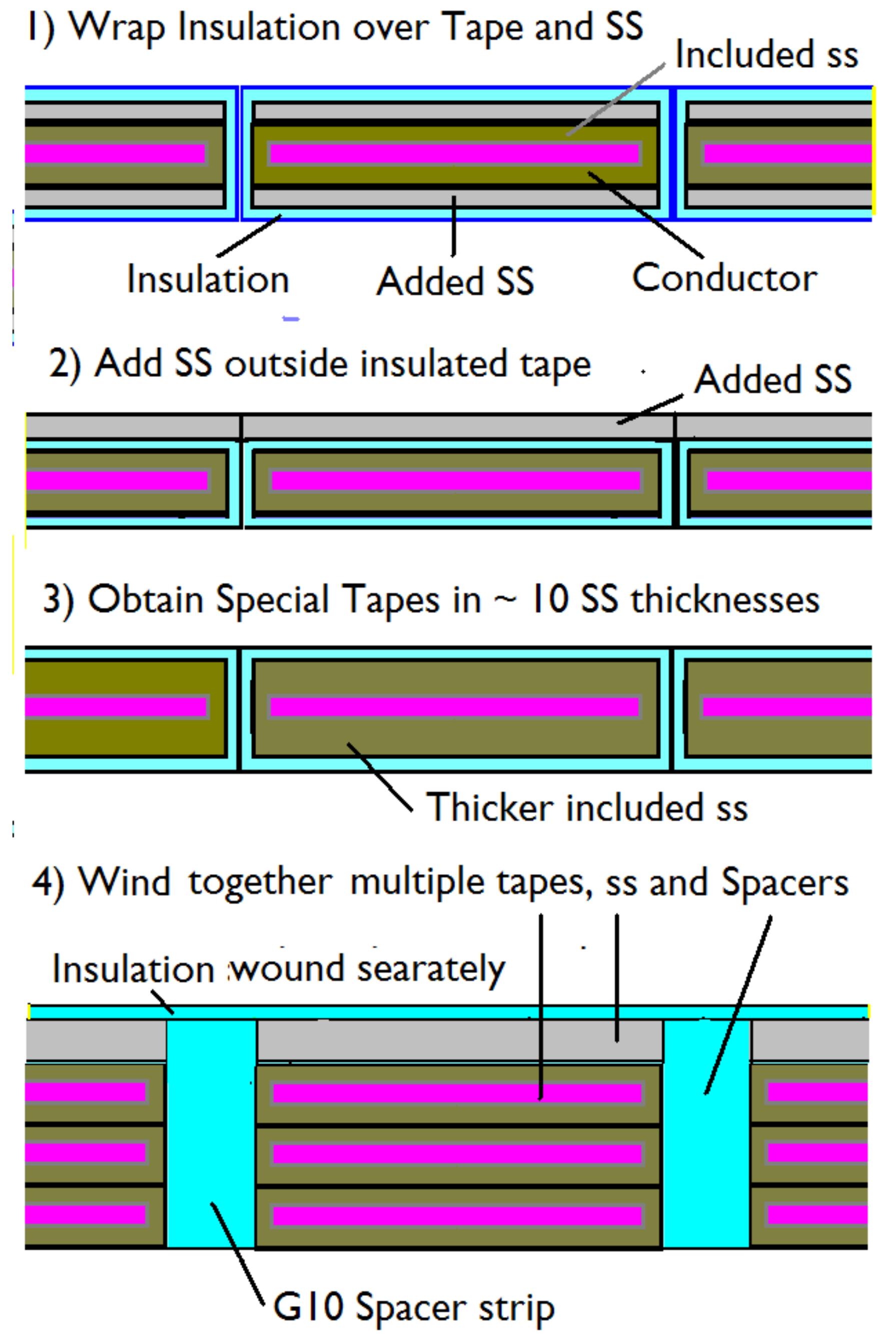
- Axial forces will compress outer layers more than inner
- Distortion will depend on Young's Modulus

- Winding in separated radial segments may be a good idea



Winding conductor SS and insulation

1. Split extra support on each side of conductor with insulation wound over all 3
   May be difficult
2. Wind extra support over insulated tape
   Transverse loads not transfered to SS
3. Use special tape with adjusted thicknesses
   Best Solution for (.27 x 4.3 mm) BSCCO ?
4. Wind multiple tapes, SS and spacer strips, then insulation
   Allows fewer leads
   Best solution for very thin (.1 x 12 mm) YBCO ?



Cooling

- Helium bath prefered if tape is hermetic
- Alternative conduction cooling
  - Insert copper strips periodically between windings, or
  - Insert thin tubes periodically between windings
- Needs study

2) Design with Increased Stability

- For additional conservatism one might want to increase stability by lowering the current density in the stabilizer.
- If Copper is added to lower the copper current density from 500 to 250 A/mm^2, then:
  - The radius rises from 36.5 to 39.6
  - The stored energy rises from 59 to 63 MJ: not large increases.
  - The needed ramp down time would rise from 1 to 4 seconds, easing the active ramp down voltages or reducing the number of leads by 4.
  - The pressures fall from 130 MPa to 116 MPa.

3) Design for 60T

- Using all other parameters as in #2 Modified Design
  - Radius now 64.4 cm vs 36.5
  - Length of outer coils extended to 160 cm (140) to keep pressure $\leq 130 MPa$
  - 2 layer voltage on ramp down now 9 kV (2.1 kV)
  - Stored Energy now 210 MJ (59)

This still seems possible, but is a much harder magnet

4) 50 T using YBCO Tape

- Copper stabiizer added to keep $j_{Cu} \leq 400 \ \ (\mathrm{A/mm^2})$
- Smaller Radius: 30 cm 36.5
- Lower stored energy: 37 MJ 59 MJ
- Lower Voltages (because wider tape) : 0.7 kV 2 kV
- But no cost yet

Summary Table

Case	B T	Pressure MPa	j(stab) A/mm^2	Rad cm	Outer L cm	Layer V kV	HTS cost M$	Mag Energy MJ
0) Starting	48	360	513	23.9	100		1.2	28
1) Modified #1	50	130	430	36.5	140	2.1	1.6	59
2) More stabilizer	50	116	250	39.6	140	2.1	1.6	63
3) 60 T	60	130	513	64.4	160	9	4.0	210
4) YBCO	50	123	400	30.0	140	0.7		37

Conclusion

For 50 T

- With the existing American Superconductor HTS tapes:
  - The quoted "starting" design is probably unrealistic from force considerations
  - Addressing these problems raises the overall magnet radius from 23 to 36 cm
- Adding stabilizer increases r, using YBCO reduces it

For 60 T

- With the existing American Superconductor HTS tapes:
  - the required radius rises to near 64 cm
  - This would be expensive, but probably still possible
- This would be better with YBCO

Parameters needed for this magnet design

- For the HTS (and Nb3Sn) design:
  - Maximum Current density vs B up to 50 (15) T as a function of field direction
  - Consistency of parameters, availability of lengths (350 m)
  - Young's modulus of tape in side and longitudinal directions
  - Sensitivity to stresses in all three directions and bending
  - Maximum pressures allowed on insulation
- For quench protection:
  - Conductor resistance vs temperature vs B up to 50 T, continuously from 4 deg to room temperature
  - Thermal conductivity between turns and layers for quench propagation
  - Voltage holding of insulation
  - Diode specifications if method #4 adopted